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Detection of the motor points of the abdominal muscles

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Abstract

Purpose: Abdominal Functional Electrical Stimulation (AFES) is a technique intended to improve respiratory function in tetraplegia where breathing is affected due to abdominal muscle paralysis. Although it is known that optimal muscle contraction is achieved when electrical stimulation is applied close to the muscle motor point, AFES studies have used a variety of electrode positions. This study aims to investigate the feasibility of using Neuromuscular Electrical Stimulation to detect the motor points of the abdominal muscles, and to evaluate the intrasubject repeatability and intersubject uniformity of their positions, to find the most suitable AFES electrode location.

Methods: Low frequency stimulation (0.5 Hz) was applied to the abdominal muscles of 10 able bodied and 5 tetraplegic participants. The electrode positions which achieved the strongest muscle contractions were recorded as the motor point positions, with measurements repeated once. For 5 able bodied participants assessments were repeated after 18 months, in seated and supine positions.

Results: Intersubject uniformity ranged from 2.8% to 8.8%. Motor point positions were identified with intrasubject repeatability of <1.7 cm, deemed adequate relative to standard AFES electrode size. Intrasubject repeatability shows motor point positions changed little (<1.7 cm) after 18 months but varied between seated and supine positions with repeatability of up to 3.1 cm.

Conclusions: A simple technique to locate the motor points of the abdominal muscles is presented and shown to have an adequate intrasubject repeatability, enabling the optimum AFES electrode location to be identified for each user.

Key words: Abdominal; Electrical stimulation; Motor point; Respiratory; Spinal cord injury

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Abbreviations

AFES: Abdominal Functional Electrical Stimulation

EO: External Oblique

FES: Functional Electrical Stimulation

NMES: Neuromuscular Electrical Stimulation

RA: Rectus Abdominis

1 Introduction

Neuromuscular Electrical Stimulation (NMES) is a method of applying short electrical pulse trains to a motor nerve, causing contraction of the associated muscle. The term Functional Electrical Stimulation (FES) is used when NMES aims to restore lost or damaged function (Moe and Post, 1962), caused by neurological damage such as that resulting from stroke or spinal cord injury.

An injury to the cervical region of the spinal cord can lead to paralysis affecting all four limbs, termed tetraplegia. In tetraplegia paralysis also affects the major breathing muscles, with the result that many people with this condition have poor respiratory function. Respiratory infections associated with this poor respiratory function are a leading cause of rehospitalisation for this population (Cardenas et al, 2004). For most people with tetraplegia exhalation is compromised due to paralysis of the abdominal muscles, affecting cough and forced exhalation. Transcutaneous FES applied to the abdominal muscles, termed Abdominal Functional Electrical Stimulation (AFES), has been shown to improve respiratory function in this population (Butler et al, 2011; Gollee et al, 2007; Langbein et al, 2001; Lee et al, 2008; McLachlan et al, 2013; Taylor et al, 2002). These studies have used a variety of empirically derived electrode locations, designed to stimulate the Rectus Abdominis (RA) and/or External Oblique (EO) muscles.

When using transcutaneous FES the most robust muscle contraction, at the lowest stimulation level, can be achieved when the stimulating electrodes are located at the motor point, defined as the point on the skin above the muscle where an electrical pulse applied transcutaneously evokes a muscle twitch with the least injected current (Gobbo et al, 2014). Gobbo et al (2011, 2014) have shown that placing the electrodes at the motor point maximises force output and minimises discomfort. Botter et al (2011) suggest that motor point charts, such as those often provided with an FES device, may be too general to enable accurate identification of the precise motor point location for an individual to achieve a consistent muscle contraction across a group. This conclusion was reached after using NMES to identify the position of the motor points of muscles in the leg and finding that these motor point positions had generally poor intersubject uniformity.

While anatomical charts showing the location of the motor points for the limbs have long been available (Reid, 1920), less information is available about the motor points of the abdominal wall muscles. Bell et al (2007) studied the anatomical structures underlying the sites at which AFES is usually applied. They found that, although the electrode location approximately corresponded to the location of the neuromuscular structures innervating the abdominal muscles, there were significant differences in these structures in different subjects. The location of the motor points of the abdominal muscles, how they vary between subjects and whether they are time and posture dependent has not been investigated in detail. This information would be useful in optimising the electrode placement in AFES, and could help to understand variations in the effectiveness of AFES in different settings.

In this study NMES was used to identify the positions of the motor points of the abdominal muscles in able bodied and tetraplegic participants. The aims of this study were (i) to assess the feasibility of using NMES to detect the position of the motor points of the RA and EO muscles and the repeatability of this technique, (ii) to evaluate the intersubject uniformity of these motor point positions, and (iii) to evaluate how the motor point locations depend on posture and whether they vary with time.

2 Methods

2.1 Participants

Ten able bodied (5 males, age 29.5±7.9 years (mean± standard deviation) (range 24 to 40 years)) and five tetraplegic participants (demographics shown in Table 1) were recruited. The tetraplegic participants, who were sub-acute inpatients at a university teaching hospital, were able to breathe independently, but had no useful abdominal muscle movement resulting in reduced respiratory function. The study was approved by the relevant local ethics committees and all participants gave written informed consent.

2.2 Motor point detection

A virtual line was taken superiorly from the highest point of the iliac crest (top of the hip bone) until reaching the costal margin, with this distance used as the reference measurement in the superior direction (yn). The lateral distance between the umbilicus and this virtual line was taken as the reference measure in the lateral direction (xn).

Table 1: Tetraplegic participant demographics. AIS = American Spinal Injuries Association Impairment Scale. AIS score refers to the function and sensation below the injury level: A – no motor function or sensation, B – no motor function with sensation, C – severely compromised motor function with sensation.

ID	Sex	Age (years)	Injury level	AIS score	Time post injury (days)
1	M	77	C3/4	C	31
2	M	24	C5/6	A	52
3	M	32	C5	B	46
4	M	20	C5	C	29
5	M	24	C5/6	C	19

Both measurements, performed on the right hand side of the body as illustrated in Figure 1, were recorded using a measuring tape and assumed to remain fixed throughout each assessment. They were therefore used to normalise motor point positions in the corresponding direction to allow intersubject comparison.

Figure 1: Diagram of reference and motor point position measurements. A virtual line was taken superiorly from the highest point of the iliac crest until reaching the costal margin. The superior length of this line (yn) and its lateral distance from the umbilicus (xn) were used as reference measurements for motor point positions. Motor point positions were normalised with respect to these distances. The white arrows illustrate the definition of the superior (y) and lateral (x) position of a motor point (represented by the white circle).

The experimental setup is shown in Figure 2. To locate the motor points, a bar electrode (MLADDF30, ADInstruments, New Zealand) with two 9 mm diameter electrode contacts and 30 mm spacing between the contacts was used. Electrolytic gel was applied to the electrode to aid the transfer of current to the skin. To locate the position of the motor points of the EO muscles, the bar electrode was positioned horizontally, inferior of the costal margin. A neuromuscular stimulator (Rehastim v1, Hasomed GmbH, Germany) was used to apply single biphasic stimulation pulses, at a frequency of 0.5 Hz with a pulsewidth of 100 µs. The current was adjusted on a participant by participant basis (20 to 60 mA). The bar electrode was moved laterally until the observed muscle contraction was strongest. This point of maximum contraction, determined visually and from participant feedback, was recorded as the motor point position. To locate the motor points of the RA muscles, the electrode was positioned vertically, approximately 3 cm lateral of the umbilicus, and moved laterally and superiorly until the strongest muscle contraction was observed. This procedure was performed on both sides of the body, with the order in which each motor point was located being randomised. The position of each motor point was measured superiorly from the highest point of the iliac crest (y) and laterally from the umbilicus (x), as illustrated in Figure 1. The same researcher recorded the motor point positions for all participants, using the same measuring tape. This procedure took approximately two to five minutes.

Figure 2: Diagram of experimental set up, with the inset showing the dimensions of the bar electrode used to apply stimulation. To detect the position of the motor point of the respective muscles, the electrode was placed on the abdomen and moved until the greatest contraction of that muscle was observed.

Able bodied participants were initially asked to attend one assessment session (A1). Each participant was asked to sit in an upright position and the landmark measurements and motor point positions were recorded. The measurements or the motor point positions were repeated after a rest period of approximately 30 minutes, during which time participants were free to walk around. The total duration of the session, summarised in Figure 3a, was approximately one hour.

a) Able bodied.

b) Tetraplegic.

Figure 3: Experimental protocol showing periods of anatomical measurements, motor point detection and rest for the able bodied and tetraplegic participants.

For the tetraplegic participants the same motor point detection procedure was used, but this was conducted at the participant's bedside, with participants in a supine position due to the acute stage of their spinal cord injury. For these participants the procedure was repeated after three days as shown in Figure 3b. Both measurements are referred to as assessment T1.

Five of the able bodied participants (3 males, age 28.8±7.4 years (mean± standard deviation) (range 25 to 42 years)) were recalled after an 18 month period, and the assessment procedure repeated. Motor points were detected with the participants in both an upright seated (A2) and supine (A3) position. The assessments are summarised in Table 2.

Table 2: Summary of assessment procedures.

Assessment	Participant	Posture	Repeat	Time of assessment
A1	Able bodied	Seated	30 minutes	Baseline
A2	Able bodied	Seated	30 minutes	18 months after A1.
A3	Able bodied	Supine	30 minutes	18 months after A1.
T1	Tetraplegic	Supine	3 days	Baseline

2.3 Statistical Considerations

Motor point positions are reported as absolute positions in the superior (y) and lateral (x) direction and as percentage values normalised by the corresponding reference distance, as described above. For each assessment session, the mean of the two measurements is taken as the motor point position for each participant, and the mean values (± standard deviation) across all participants are reported for the absolute and normalised results. The standard deviation of the normalised results was used to describe the uniformity across all participants. A Student's independent t-test was used to test for a statistically significant difference ($p<0.05$) in the group motor point positions recorded at A1 and T1.

To assess the repeatability of measurements, the coefficient of repeatability (CoR) was calculated as 2 times the standard deviation of the difference between two measurements, across all participants, giving a 95% confidence range (Bland and Altman, 1986).

The repeatability of the motor point detection technique was assessed by calculating the CoR for the two repeat measurements taken at each assessment session, across all participants. The dependency of motor point position on time was evaluated by calculating the CoR between the motor point positions recorded for each participant at A1 compared to those from A2 (18 months later), for those participants who took part in both assessment sessions. Whether motor point positions changed with posture was assessed by calculating the CoR between the motor point positions recorded for each participant at A2 (seated) with those at A3 (supine).

3 Results

The normalised locations of the motor points of the RA and EO recorded at A1 (able bodied, black symbols) and T1 (tetraplegic, grey symbols) are shown in Figure 4. Figure 4a depicts the motor points for each participant (taken as the mean of the two repeat measurements). Figure 4b shows the normalised motor point positions for each muscle, grouped by assessment. While the median motor point positions of the EO muscles are in approximately the same normalised position for both assessment groups, the range of the positions when measured superiorly from the iliac crest line was relatively large. For the RA muscles, the positions of the two assessment groups are different in both the lateral and superior directions. Also shown are the normalised locations of the umbilicus in the superior direction, which indicates that these also differ between both assessment groups.

The mean (± standard deviation) motor point positions recorded at A1 and T1 are shown in Table 3 as absolute and normalised measurements. It can be seen that the absolute motor point positions recorded at T1 were all statistically significantly different from the motor point positions recorded at A1 when measured from the iliac crest ($\overline{Y}$). However, when these measurements were normalised to allow for more effective comparison between groups, $\overline{Y}_n$, only the motor points of the RA muscles were in a statistically significantly different position at T1 compared to A1, with these motor points found to be statistically significantly closer to the costal margin.

a) Normalised individual motor point positions recorded at A1 (black ×) and T1 (white **o**), with the position of the umbilicus for each participant shown on the midline. Also shown are the landmarks for the reference measurements (top of the iliac crest (grey *), corresponding point on the costal margin (grey +)).

b) Normalised group motor point positions (median and inter-quartile ranges) recorded at A1 (black) and T1 (grey).

Figure 4: Individual and group motor point position of the external oblique (outer left and right) and rectus abdominis (inner left and right) muscles of ten able bodied (assessment A1, black symbols) and five tetraplegic (assessment T1, grey symbols) participants, with the position of the umbilicus shown on the midline. Motor point positions are normalised to the reference measurements shown in Figure 1.

Table 3: Mean position and standard deviation (intersubject uniformity) of the position of the Rectus Abdominis (RA) and External Oblique (EO) motor points for assessment A1 (10 able bodied participants) and T1 (5 tetraplegic participants). Results are expressed as absolute distances measured superiorly from the iliac crest ($\overline{Y}$) and laterally from the umbilicus ($\overline{X}$), and corresponding normalised distance with respect to the reference measurements ($\overline{Y}_n$ and $\overline{X}_n$), ± standard deviations s. * indicates mean at T1 is statistically significantly different to mean at A1.

Ass.	Muscle	$\overline{Y} \pm s_y$ [cm]	$\overline{X} \pm s_x$ [cm]	$\overline{Y}_n \pm s_{yn}$ [%]	$\overline{X}_n \pm s_{xn}$ [%]
A1	RA–Right	6.2±1.1	4.3±0.7	55.8±6.1	24.1±4.0
	RA–Left	6.2±1.3	4.0±0.7	55.8±4.4	22.3±2.8
	EO–Right	9.2±1.4	15.6±2.1	83.9±8.8	86.9±7.8
	EO–Left	9.1±1.7	15.6±2.3	82.3±7.3	86.7±6.3
T1	RA–Right	9.9±4.3*	4.8±0.5	66.0±5.8*	28.0±2.5
	RA–Left	9.8±4.5*	4.8±0.6	65.4±7.1*	28.1±4.1*
	EO–Right	12.6±4.3*	14.7±1.3	85.7±4.0	86.2±5.8
	EO–Left	13.0±5.0*	14.8±1.6	87.7±6.3	86.9±3.9

Table 4 shows the mean coefficient of repeatability between the two measurements of motor point position recorded at all assessments (A1, T1, A2 and A3, $\overline{\text{CoR}}$) which provides a measure of the repeatability of the measurement technique. The comparison between assessments A1 and A2 (5 common able bodied participants, 18 months apart), CoR(A1,A2), shows the repeatability of the motor point position over time, while the coefficient of repeatability between assessment A2 (seated) and A3 (supine) shows the influence of posture (CoR(A2,A3)) on the motor point position. From $\overline{\text{CoR}}$ it can be concluded that 95% of test-retest measurement differences would be less than 1.7 cm, with a similar CoR even after an 18 month period (CoR(A1,A2)). The CoR is greater if tests are performed with different postures (CoR(A2,A3)), indicating a dependence of motor point position on posture in particular for the RA muscle when measured in the superior direction (y).

Table 4: Mean coefficient of repeatability ($\overline{\text{CoR}}$) of the position of the motor points of the Rectus Abdominis (RA) and External Oblique (EO) muscles recorded 30 minutes apart for: 10 able bodied participants (A1); 5 able bodied participants after 18 months in seated position (A2); 5 able bodied participants after 18 months in supine position (A3) and 3 days apart for 5 tetraplegic participants in supine position (T1). Also shown is the mean CoR of the motor point positions recorded 18 months apart (CoR(A1,A2)) and in a seated and supine position (CoR(A2,A3)). Results are expressed as absolute distances measured superiorly from the iliac crest (y) and laterally from the umbilicus (x).

	$\overline{\text{CoR}}$		CoR(A1,A2)		CoR(A2,A3)	
Muscle	y [cm]	x [cm]	y [cm]	x [cm]	y [cm]	x [cm]
RA–Right	1.2	0.9	0.9	1.3	3.1	1.5
RA–Left	0.9	0.8	0.7	0.9	2.3	1.1
EO–Right	1.0	1.6	1.3	1.5	1.5	1.4
EO–Left	1.3	1.6	1.5	1.6	1.0	1.9

4 Discussion

In this study the feasibility of using NMES to detect the position of the motor points of the RA and EO muscles was demonstrated in ten able bodied and five tetraplegic participants. The motor points of these muscle groups could be easily detected in all participants. It was shown that these motor points have a range of intersubject uniformities, and that repeatability of their positions within subjects was adequate, both at the same assessment session and when repeated after 18 months. Variations in posture resulted in changes of the position of the motor points of the RA muscle.

The results of this study suggest that this technique can be easily adopted to reliably detect the positions of the motor points of the abdominal muscles. Owing to the fact that the abdominal muscles are often not included in standard motor point charts (Reid, 1920), and the adequate repeatability found in this study, we suggest that this technique should be adopted as standard procedure to select the optimum electrode location when using AFES to support respiration in tetraplegia. This method of motor point detection may also be beneficial to select the optimum electrode placement when using NMES to improve muscle strength, endurance and appearance in the able bodied population.

When analysing the position of the motor points of muscles in the leg Botter et al (2011) developed criteria which allowed intersubject uniformity, a measure of the spread of motor point positions across participants, to be classed as ‘good’ (<4%), ‘fair’ (4−6%) or ‘poor’ (>6%). It was found that when classifying the intersubject uniformity of the motor point position measurements recorded at assessments A1 and T1 (cf. s_{xn} and s_{yn} in Table3), 3 were ‘good’, 6 were ‘fair’ and 7 were ‘poor’. It should be noted that Botter et al (2011) based their uniformity calculations on normalising the muscles by their estimated lengths, while in this study the locations are normalised by anatomical reference measurements. Nevertheless, the range of intersubject uniformity observed here suggests that the use of standard motor point locations may not be suitable for detecting the exact location of the motor points of the abdominal muscles, agreeing with the finding of Botter et al (2011) for the muscles of the leg.

Bland and Altman (1986) recommend the CoR as a method of assessing test-retest repeatability with a 95% confidence. In this study the largest CoR between the motor point positions recorded at A1, A2, A3 and T1 were 1.6 cm for the EO and 1.2 cm for the RA muscles. Between the two measurements of motor point position compared here, no restrictions were placed on participant movement, indicating that NMES can be used to detect the position of the motor points with good repeatability, even after time and activity.

When the positions of the motor points were detected after 18 months the largest CoR was also 1.6 cm, indicating that the positions of the motor points remain relative constant over time. The electrodes typically used for AFES studies are approximately 5 cm long with a space of approximately 3 cm between the electrodes (Gollee et al, 2007; Langbein et al, 2001), meaning that the CoR would fall within this area. This suggests that use of the motor point detection technique outlined here to locate the position of the motor points once for each individual, at the start of a course of AFES, would be adequate.

Placement of the stimulating electrodes at the motor points appeared to lead to a more effective muscle contraction compared to when using empirically derived electrode locations. The effect of this should be twofold. Firstly, this should lead to a greater benefit from using AFES which may, in turn, lead to a greater improvement in the respiratory function of the user and improve their quality of life. Secondly, it should ensure a consistent muscle contraction across AFES studies.

The motor points of the tetraplegic participants were detected in a supine position due to the acute stage of their spinal cord injury. For these participants the motor points of the RA muscles, when measured in the superior direction, were statistically significantly closer to the costal margin than for the able bodied participants (cf. $\overline{Y}_n$ for RA in Table 3). This posture dependance of motor point position was further highlighted by the large CoR recorded when the motor points of five able bodied participants were detected in a seated and supine position (cf. CoR(A2,A3), Table 4). This suggests that motor point positions should be re-identified if posture changes occur.

Dyskinesia, a movement disorder causing involuntary muscle movements, has been reported to affect the abdominal muscles (Linazasoro et al, 2005). The application of Botulinum toxin A for nerve blocking has been used to treat dyskinesia (Hallett et al, 2013). For effective nerve blocking Botulinum toxin A should be applied at the motor point (Lee et al, 2009). The detection of the motor points of the abdominal muscles using the methods outlined here could aid in the application of Botulinum toxin A for treating dyskinesia of the abdominal wall.

Anatomical investigations of innervation of the abdominal muscles (Bell et al, 2007) suggest that the RA and EO muscles have more than one motor point. In this study, the focus was to detect the location where the strongest contraction was observed. For some of the able bodied participants there appeared to be a second motor point of the RA muscle, located slightly inferior to the costal margin. This motor point was not present in all participants, or could not be as easily detected as the other motor points documented. It may be situated deeper than the other motor points, or may have belonged to another muscle group situated proximal to the RA muscle. While Langbein et al (2001) used an electrode position which would have stimulated this ‘second’ motor point of the RA muscle, the difficulty of detection found here would suggest that the application of AFES at this location would not achieve a strong muscle contraction. The motor points of the EO muscle reported here were the only motor points of this muscle detected.

A potential limitation of this study was the accuracy of motor point position measurement. By using a standard measuring tape the resolution was approximately 0.25 cm which may account for some of the CoR and intersubject uniformity values which were observed. One approach to increase measurement accuracy would be to use position markers in combination with an accurate position measurement system to record the motor point positions. However, these devices tend to be large, making them impractical in a clinical setting. Additionally, previous motor point detection studies have used a pen electrode to apply stimulation (Botter et al, 2011; Gobbo et al, 2011). In this study a bar electrode, which spreads stimulation over a larger surface area, was used to minimise user discomfort. The low CoR suggests that the measurement inaccuracies did not have a major influence on accurately locating the position of the motor points.

5 Conclusion

In this study NMES was used to reliably detect the position of the motor points of the abdominal muscles. The results of this study show that while position of the motor points of the RA and EO muscles change little over time, they were found to be posture dependent, and variations were observed between participants. This motor point detection technique should enable the optimum AFES electrode location for each user to be identified, which if adopted as a standard technique for all AFES studies, would allow easier comparison of results.

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Conflict of interest

None.

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Figure 1
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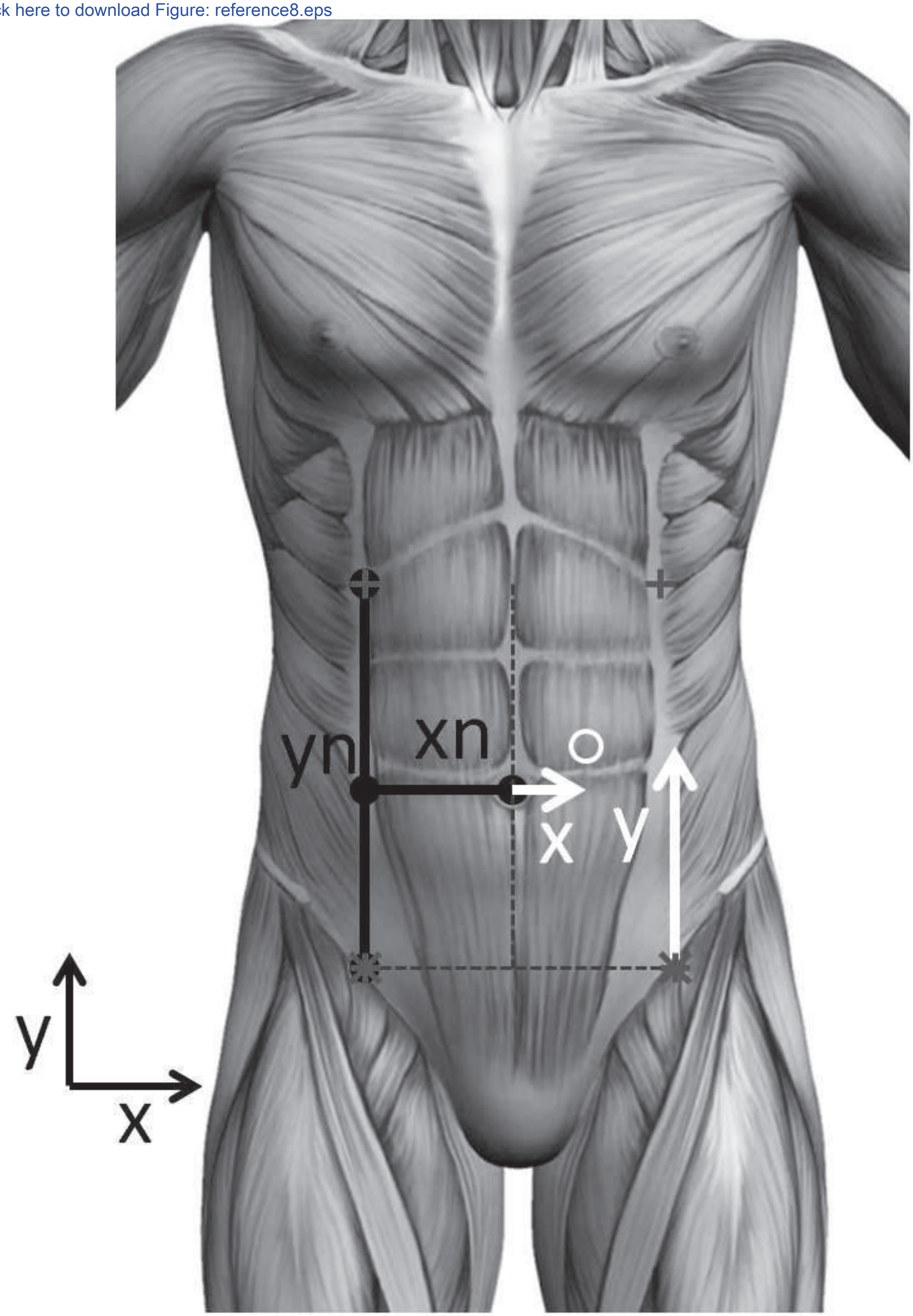

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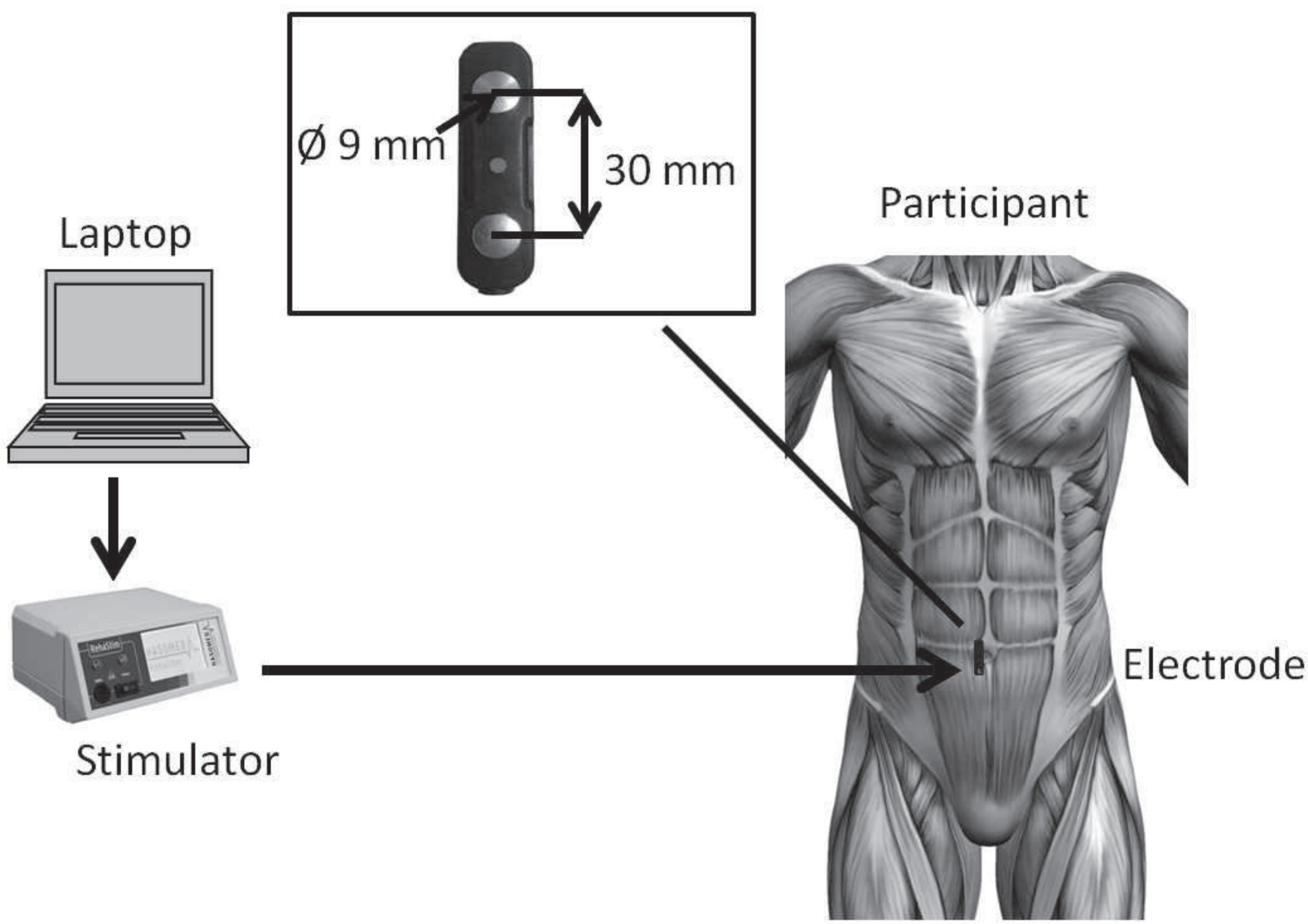

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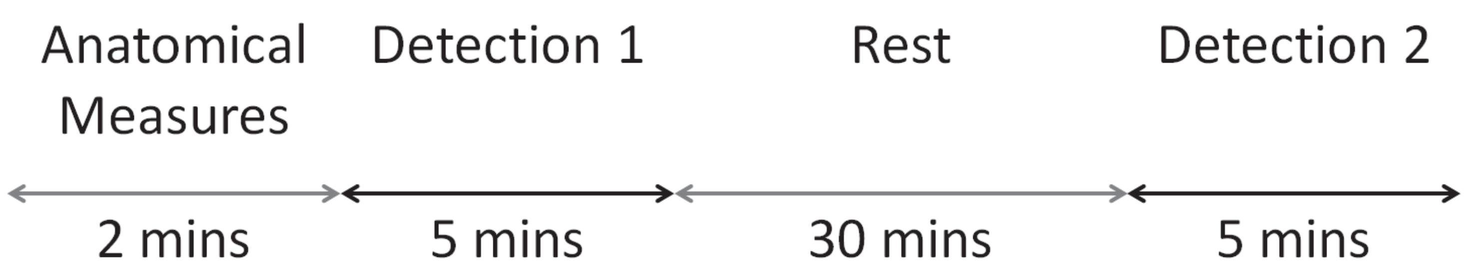

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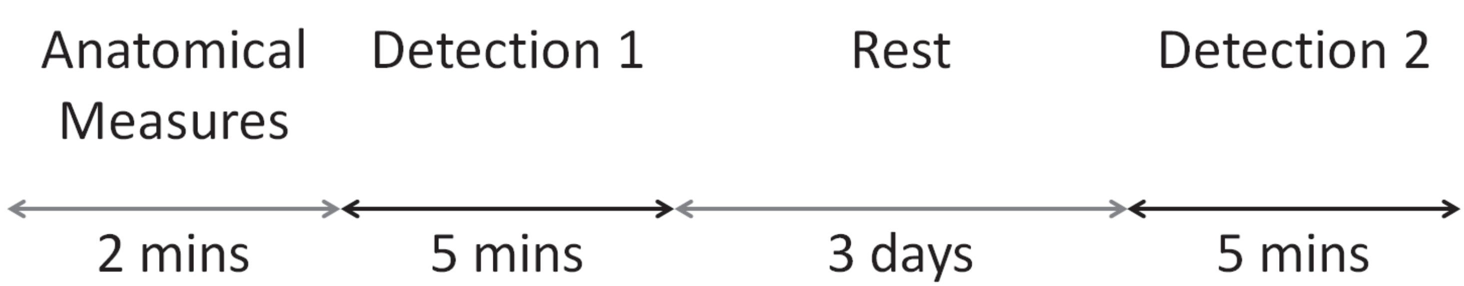

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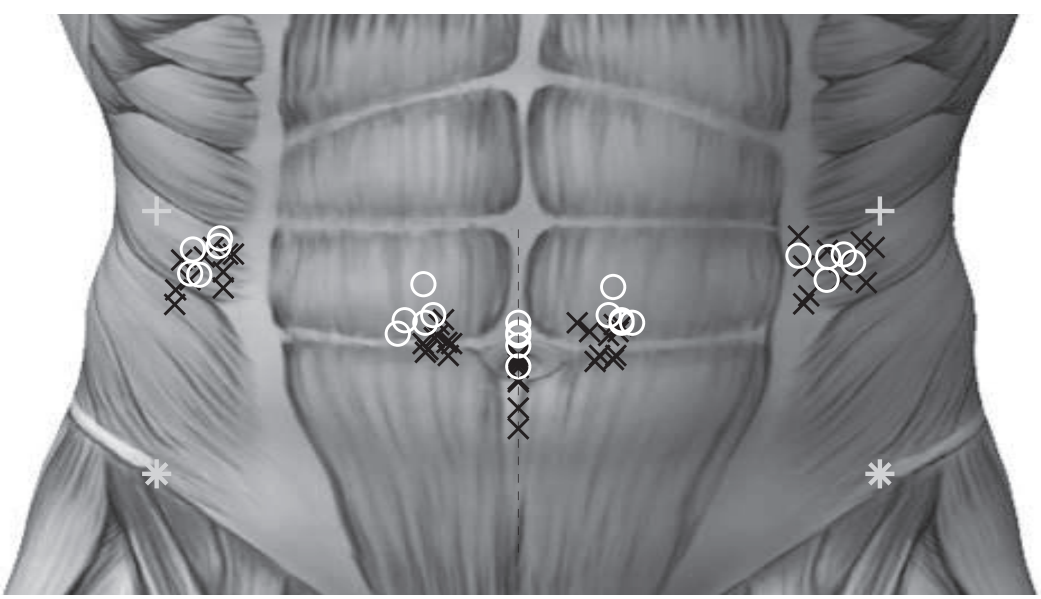

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